X-ray Surveys

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Material liberally borrowed from Richard Mushotzky, Niel Brandt, and others

Missing from talk

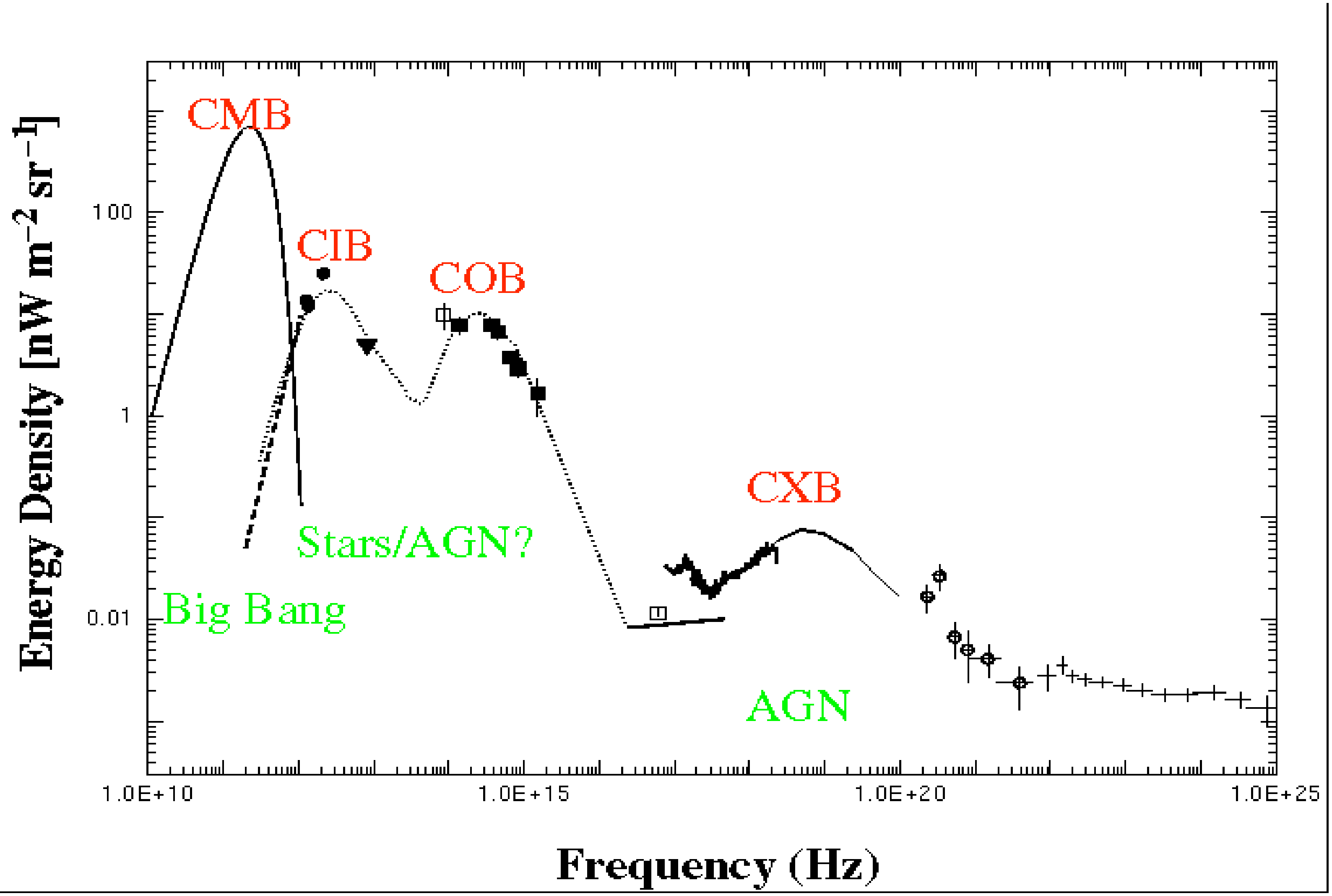
- The Galaxy (focus is extragalactic)
- Wider-field/shallower surveys at 0.2-10 keV (see P. Green talk from 2005 that focused more on wider-field surveys)
- Extended sources: note that clusters and groups of galaxies are significant populations particularly in the 0.5-2 keV bandpass, see Rosati, Borgani & Norman (2002) for galaxy cluster review and Keith Arnaud’s talk this AM
- Surveys of objects (focus here is on ‘blank-field’ serendipitous surveys of the Universe)

Good news!

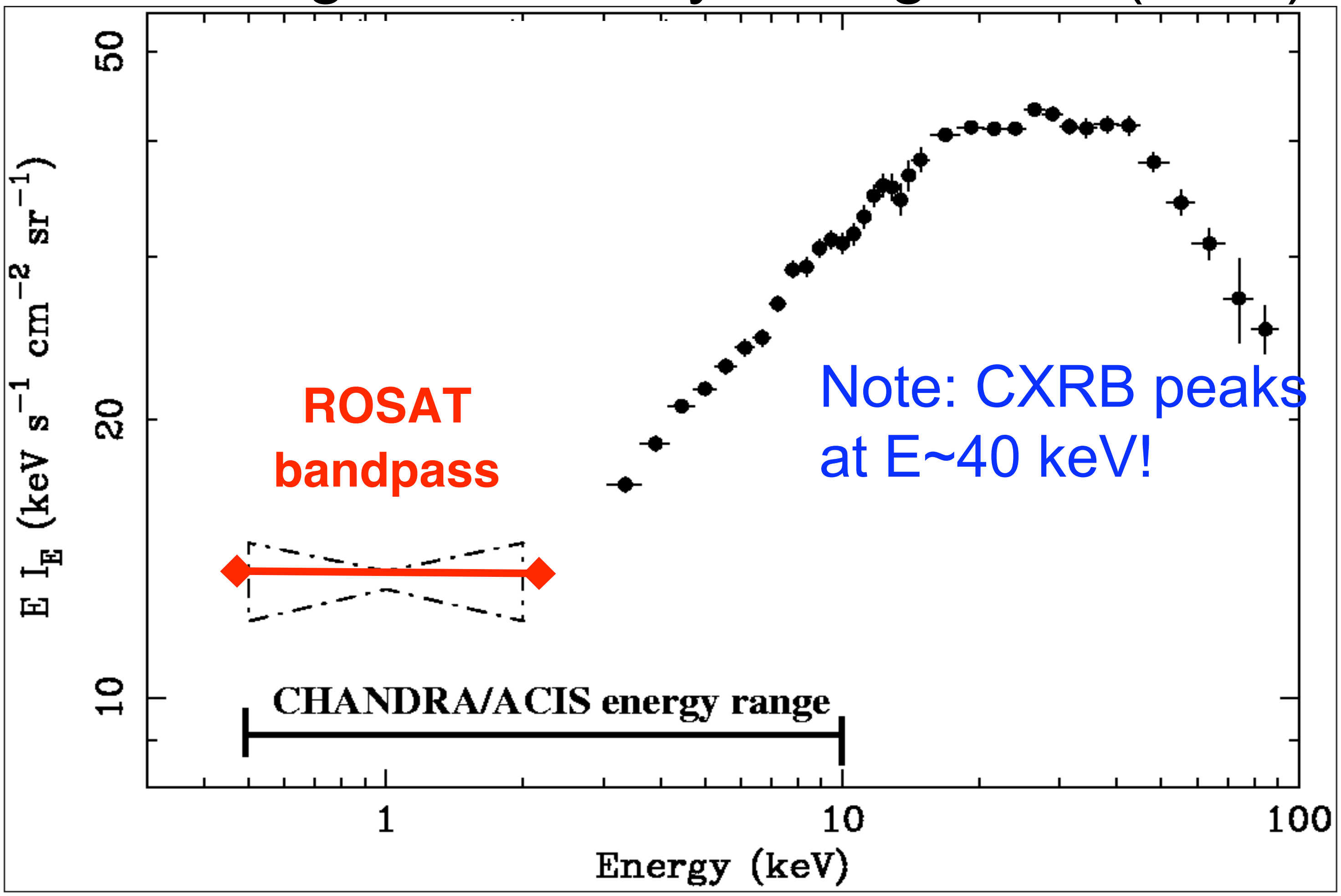
- REVIEW article on X-ray Surveys:
  - Brandt & Hasinger (2005; ARA&A, 43, pp.827-859)
- Presentations from November 2006 X-ray Surveys meeting at SAO:
  - http://cxc.harvard.edu/xsurveys06/agenda/presentations/

The spectrum of the Universe

- Extragalactic Background Studies



The Extragalactic X-ray Background (XRB)



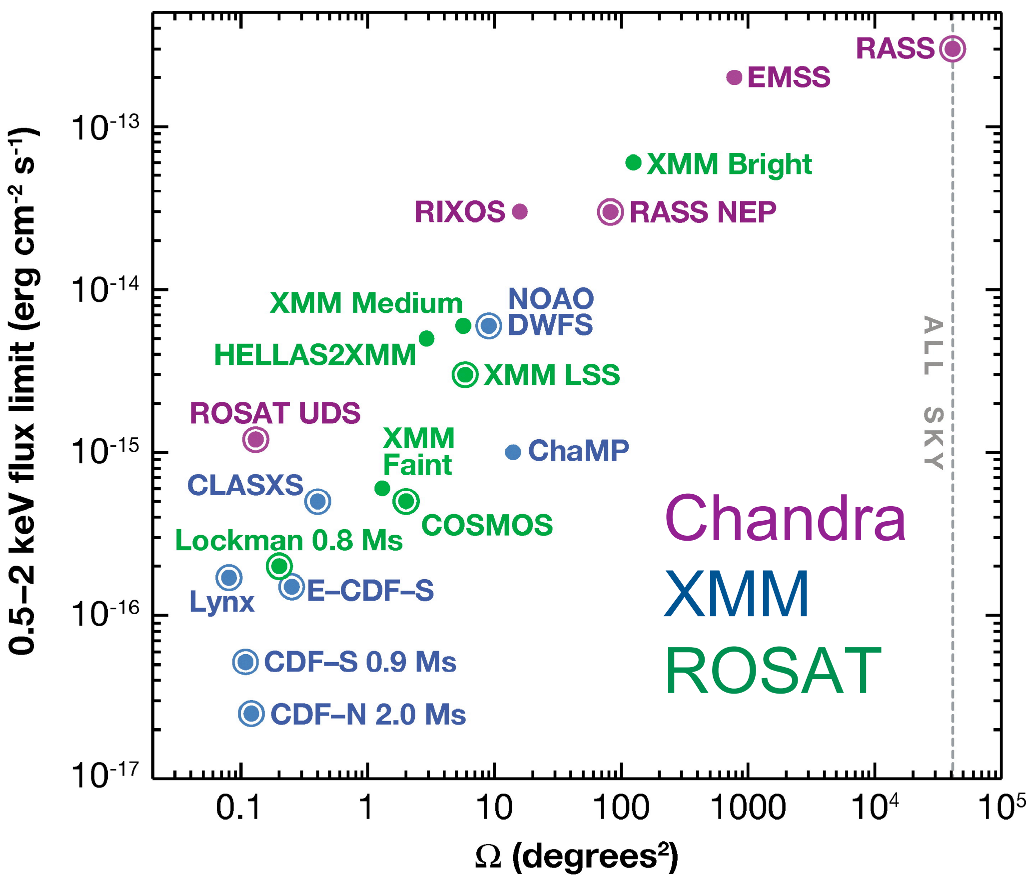
Chandra/XMM: higher-quality X-ray imaging in the 2-10 keV bandpass resolving 50-80% of this part of the XRB, closer to the energy peak.

Note that ~50% of the CXRB is resolved at E>8 keV (Worsley et al. 2005)

Existing X-ray Surveys:

Most sensitive surveys in the soft X-ray bandpass (0.5-2 keV)

Deepest X-ray surveys are truly "pencil-beam"

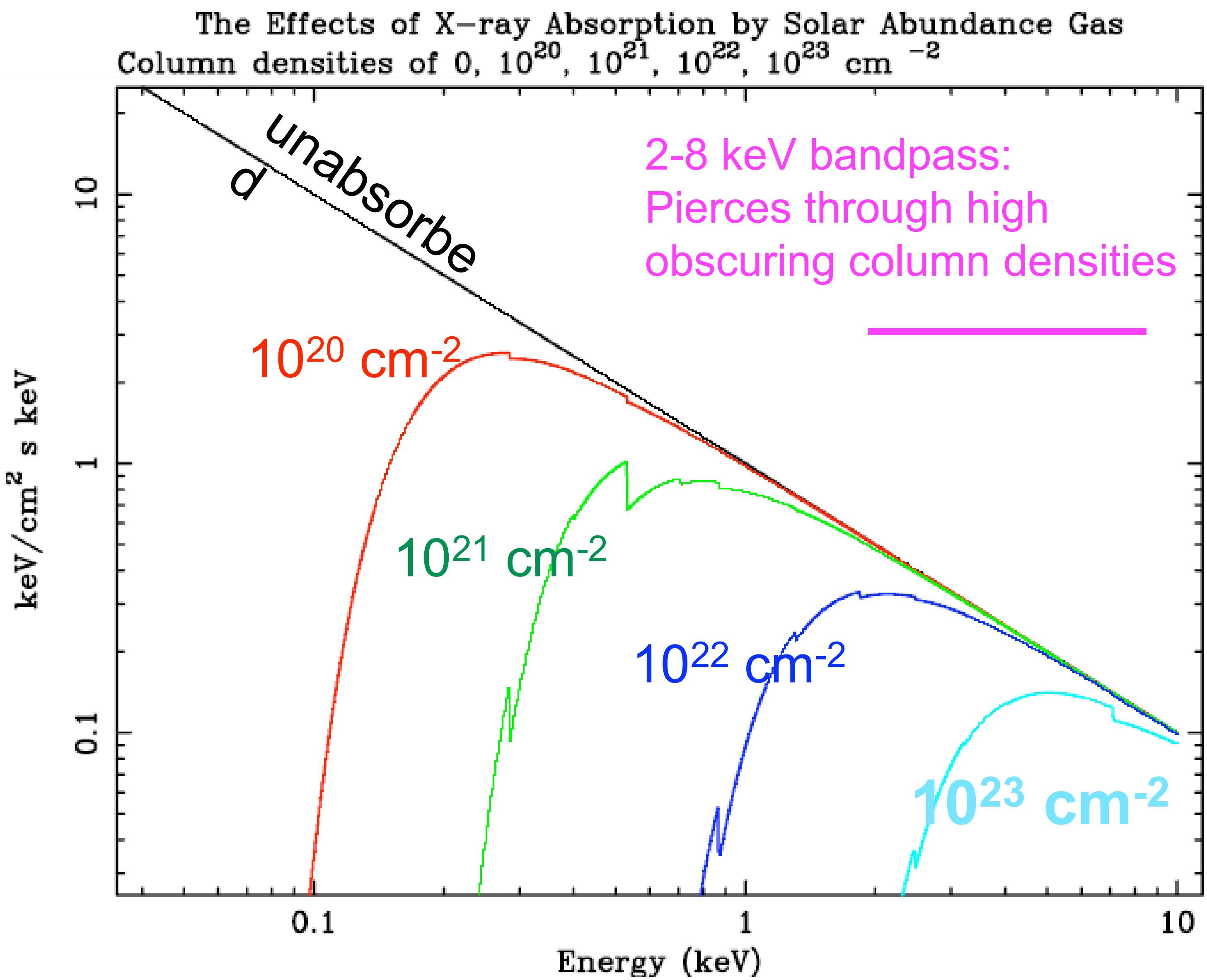


NOTE:
Very few all-sky X-ray surveys!

Brandt, WN and Hasinger, G. 2005
Annu. Rev. Astron. Astrophys. 43: 827–59

Importance of sampling hard X-ray energies

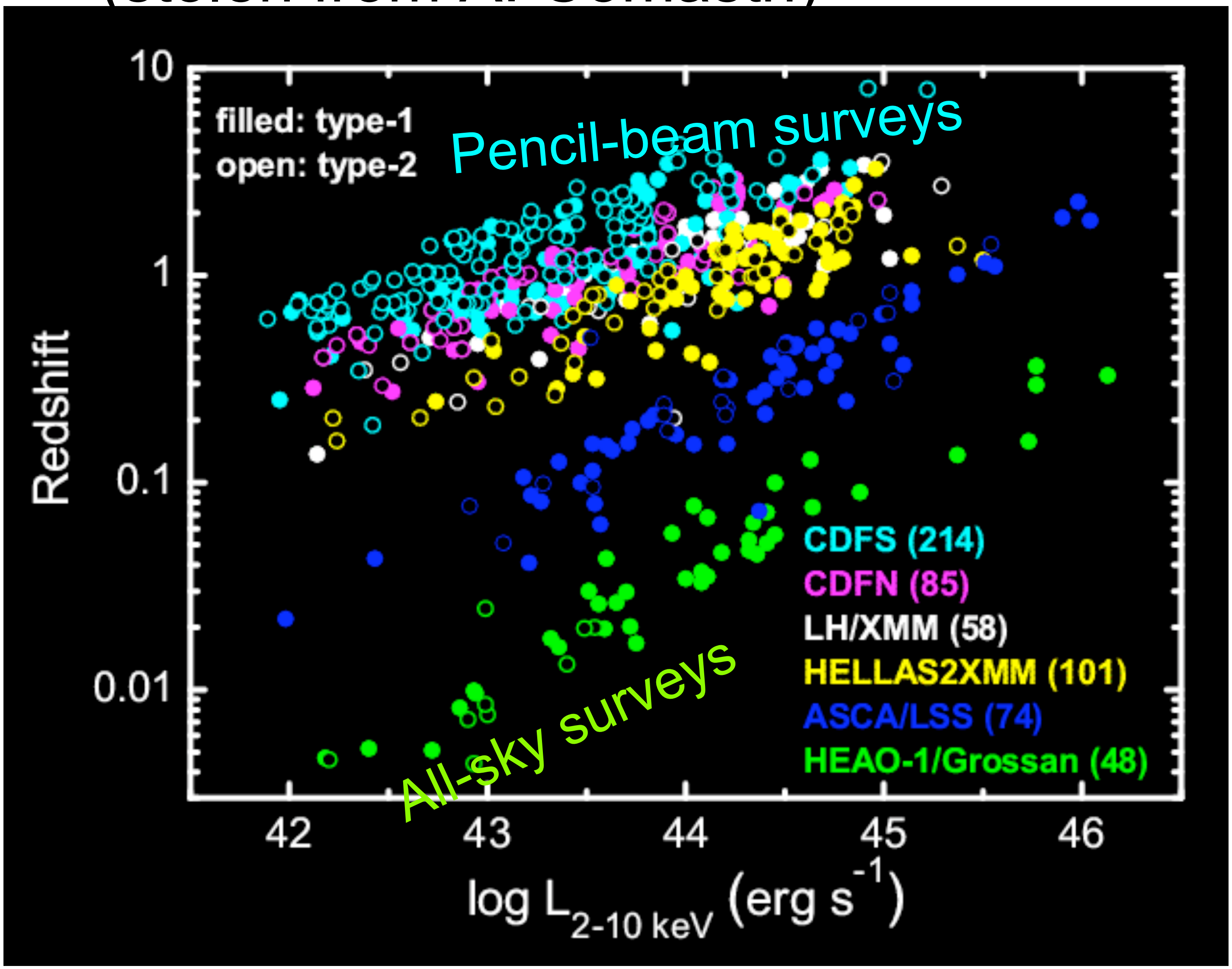
(which gets easier at higher redshift)



2-10 keV X-ray Surveys

(stolen from A. Comastri)

Census of the hard X-ray Universe requires a range of survey depths & sizes



The Swift BAT
Hard X-ray Survey

X-ray surveys at E>10 keV

- We simply have not accounted for the vast majority of the accretion energy budget of the Universe (the CXRB is <5% resolved at hard energies)
- There is some chance of wide-field moderately sensitive hard X-ray survey missions going up in ~5 years from now (big breakthrough portion of EM spectrum)

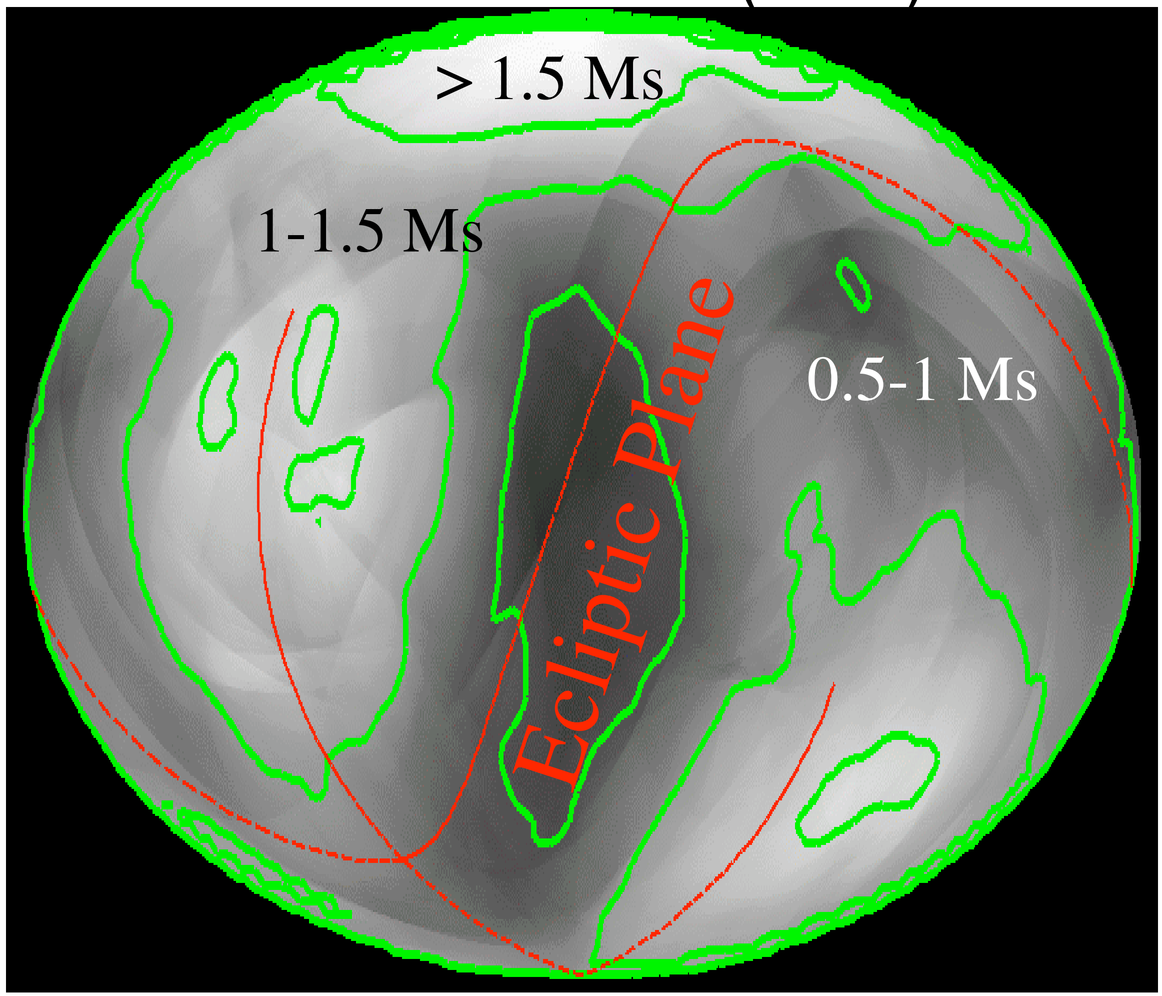
Great leap forward in hard X-ray surveys: the Swift BAT Survey

- 10X more sensitive than HEAO-1 A4; Levine et al. 1984
- **Piggy-backed on Swift GRB observing plan)**
- **Energy Range 14 - 195 keV**
- **Spatial Resolution 21' sky pixel, centroided to <1-3'**

FIRST 9 MOS:

- survey of whole sky complete at ~4×10^{-11} ergs cm^{-2} s^{-1}
  - 155 galactic sources
  - 147 AGN
  - 20 other sources

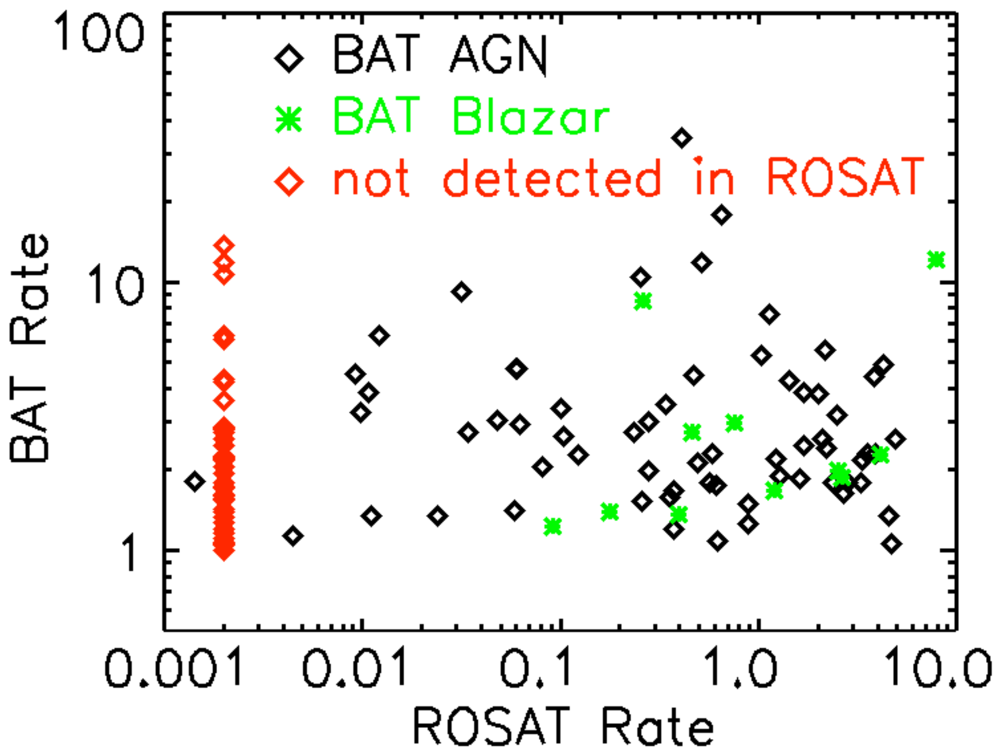
Markwardt et al. (2005)

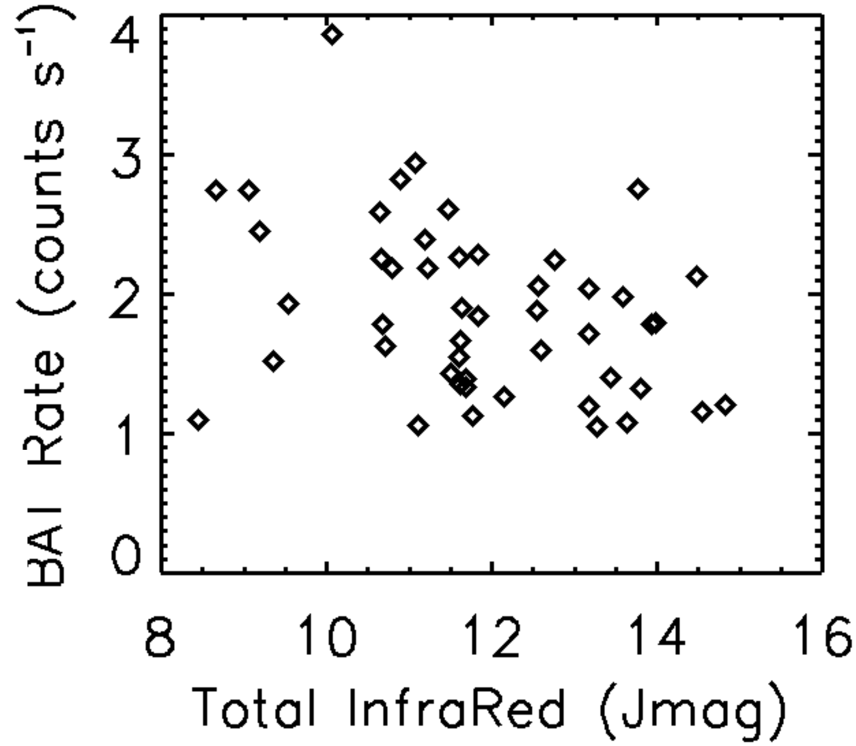


Exposure time after 9 months of operations

Selecting AGN via hard X-ray emission

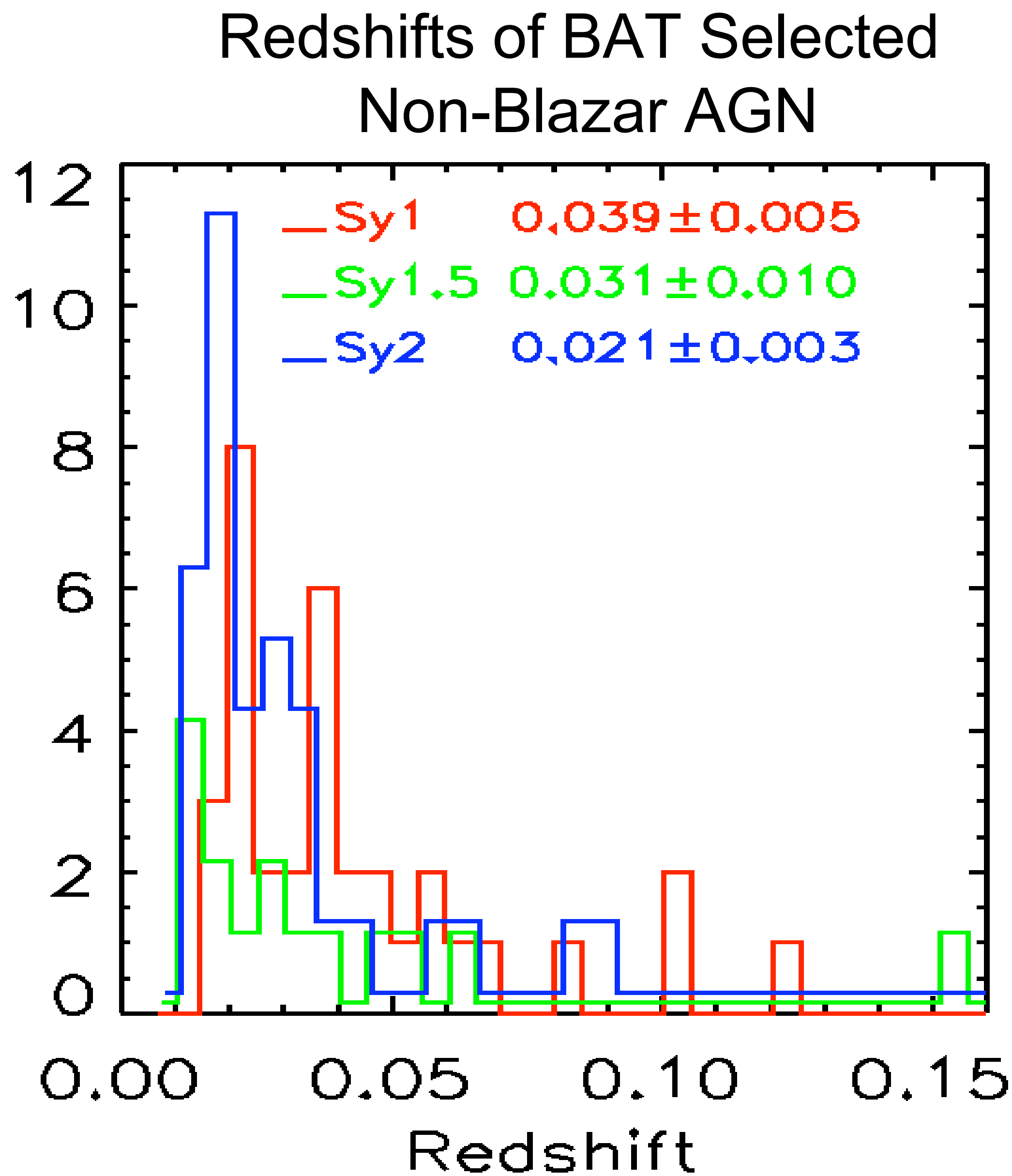
- no correlation between BAT and ROSAT count rates
- 44 BAT sources not detected by ROSAT





- no correlation with total 2MASS J band
- soft x-ray and IR do not measure true AGN luminosity or complete populations

Swift BAT AGN Survey



Deep X-ray Surveys

Deep X-ray Surveys

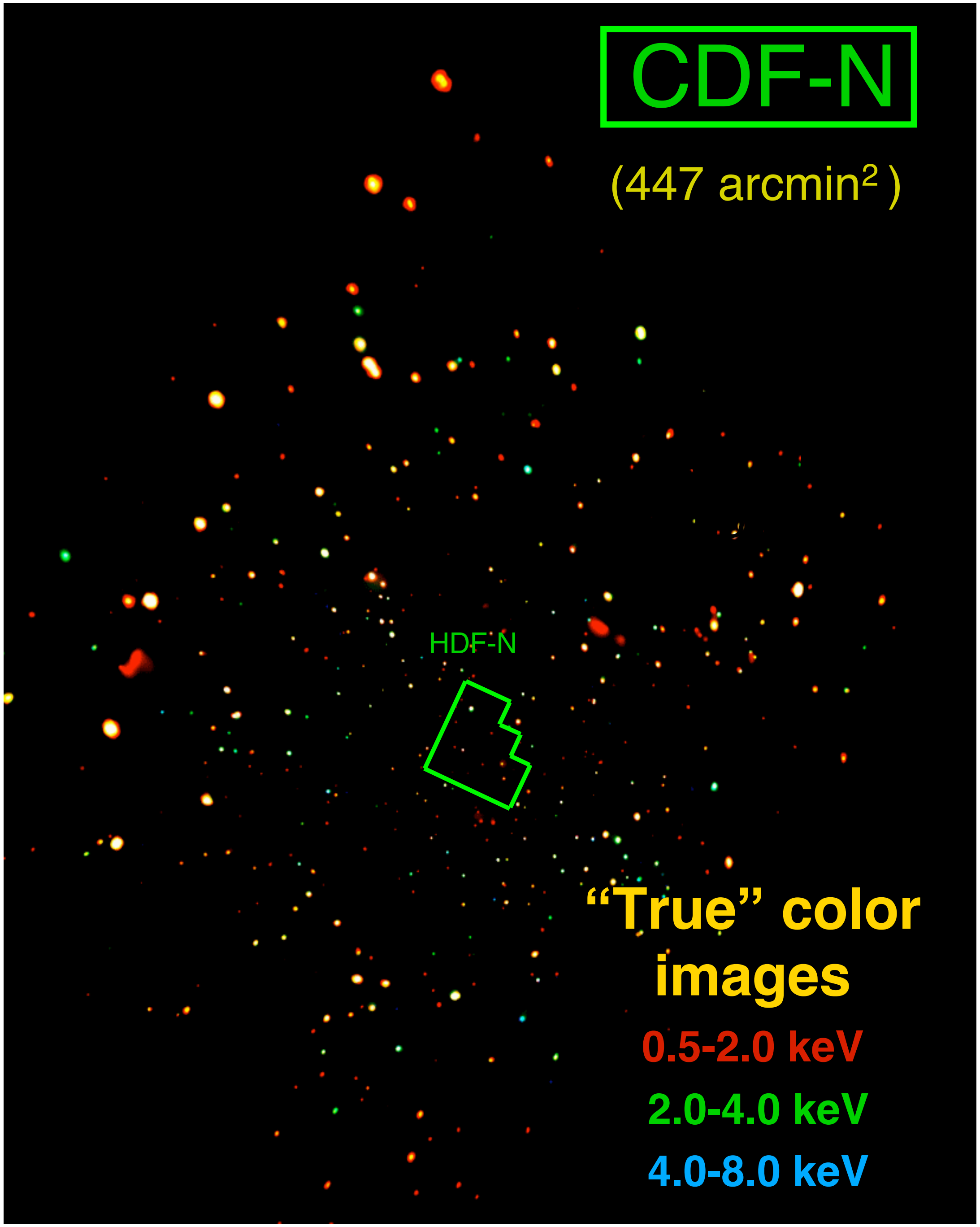
- Science focus: formation and evolution of cosmic building blocks, including galaxies and supermassive black holes
- Probe intrinsically less luminous and more typical objects than wide-field, shallower surveys.

The deepest X-ray survey (CDF-N)

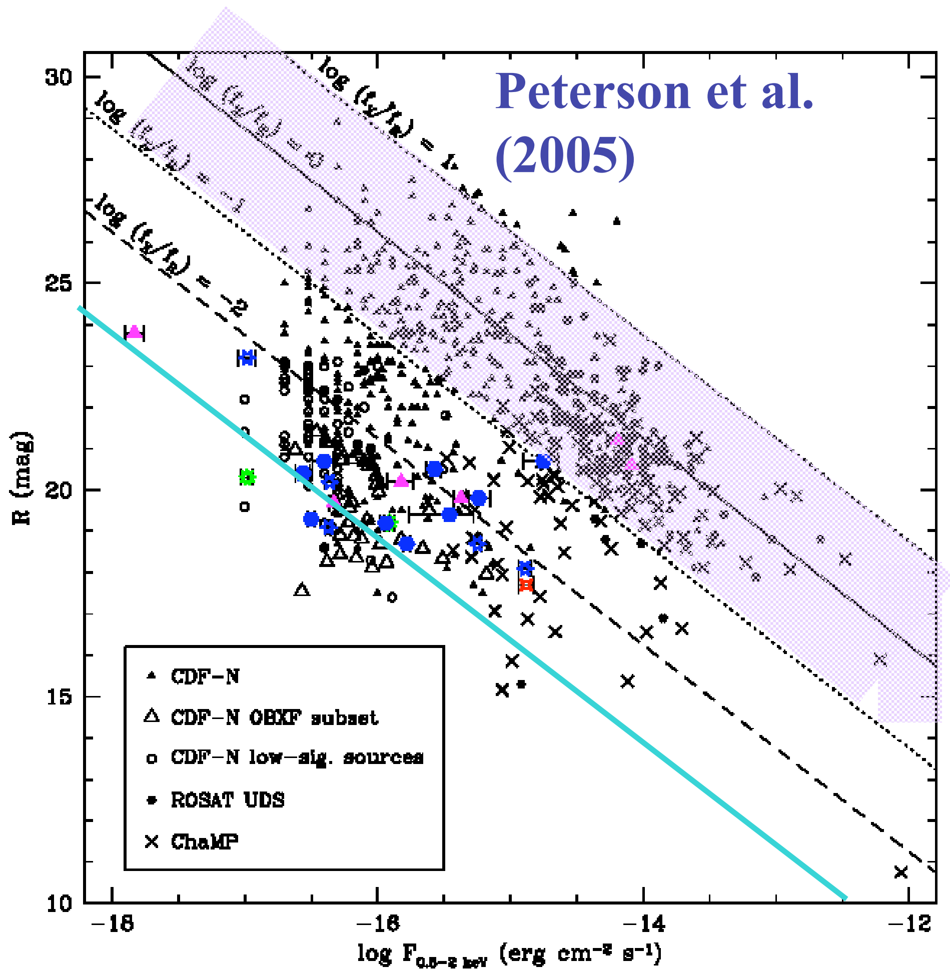
Alexander et al. 2003

Chandra allows for:
More sensitive X-ray surveys due to sub-arcsecond imaging capability (deepest and highest-redshift objects)

XMM allows for deep harder X-ray (5-10 keV) surveys (higher collecting area than Chandra in 8-12 keV bandpass)



What are these X-ray sources?

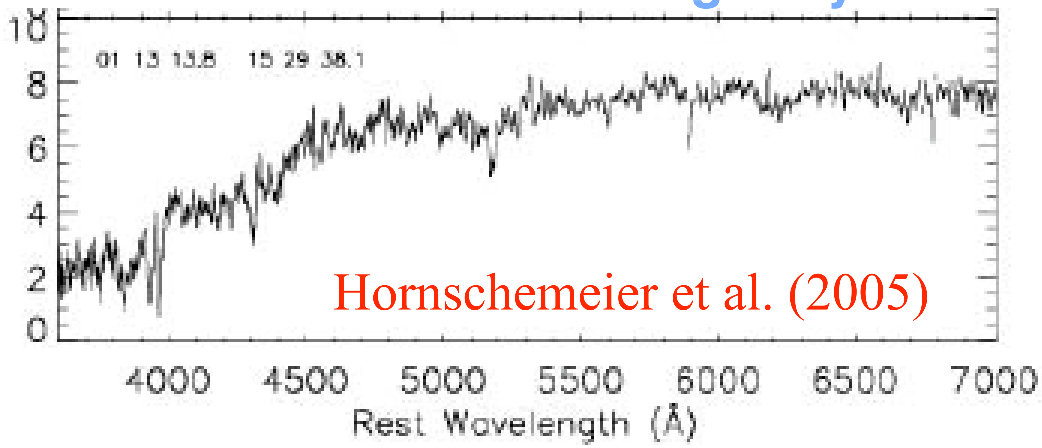


- Classification using:
  - spectroscopic ID
  - X-ray spectra ($N_H > 10^{22}$ cm^2 OR $\Gamma<1$)
  - $L_{X,AGN} > 3 \times 10^{42}$

Problems
  - Optical faintness of sources prevent collecting spectra
  - X-ray 'spectra' are really just single-band detections! (or maybe a hardness/band ratio)
  - Some X-ray luminous galaxies may be expected at earlier times when the average SFR was higher

Optical spectra for dividing AGN from SB

"Passive" SDSS Optical Spectrum for a Chandra-detected galaxy

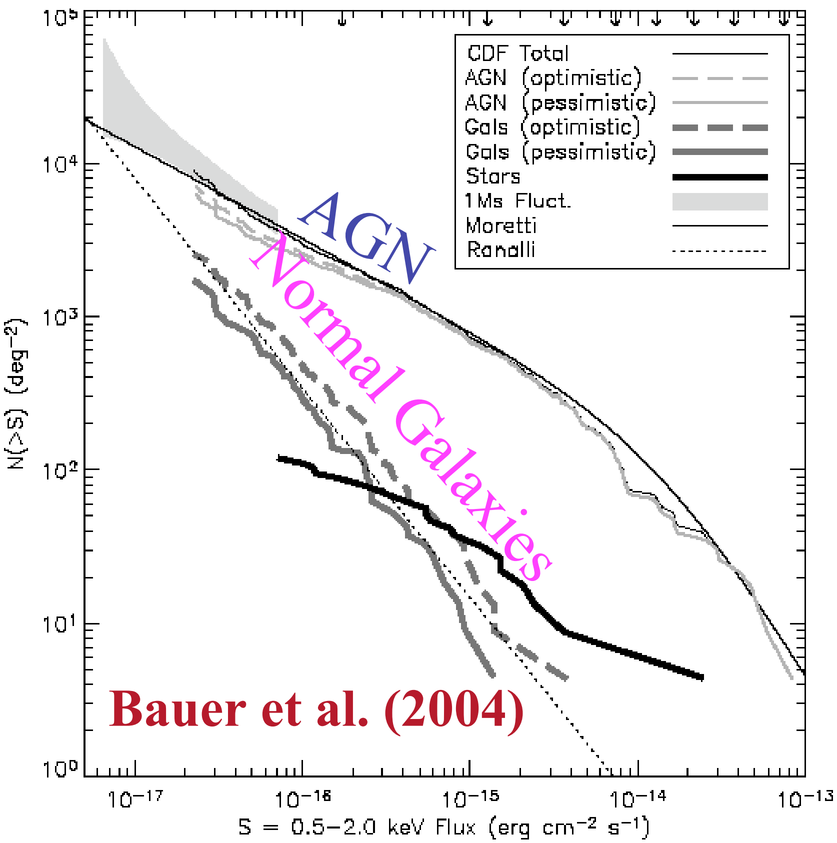


- Many X-ray background sources lack clear signatures of AGN in their optical spectra (i.e., XBONGS; Comastri et al. 2002)

- Possible reasons for missing AGN features
  – X-ray emission dominated by non-AGN emission (e.g., Hornschemeier et al. 2005)
  – Optical or X-ray dilution (e.g., Moran et al. 2002; Peterson et al. 2005)
  – Evolution of NLR at low-luminosities (e.g., HST work of Barger et al. 2003)

Number Counts & the CXRB

(see P. Green's 2005 talk for general Log N - Log S equations)

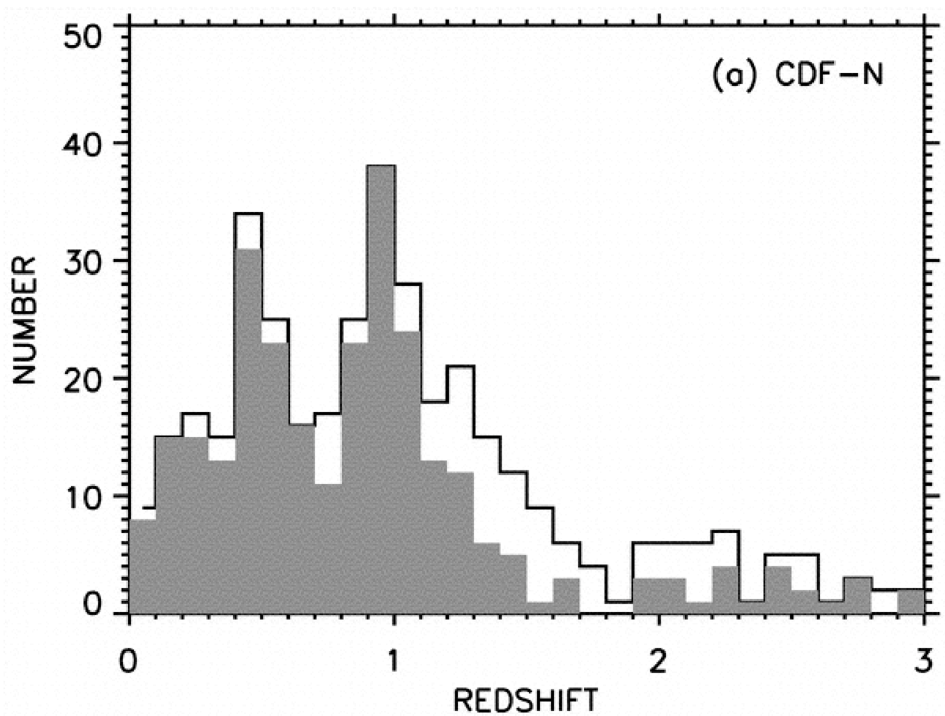


"Blank" field log*N*-log*S* from 1-2 Ms Chandra Deep Fields

- Number counts well-measured over 4 orders of magnitude in 0.5-2.0 keV flux (down to ~2.5 ×10^{-17} erg cm^2 s^{-1}(0.5 –2keV) **(Hornschemeier et al. 2003; Bauer et al. 2004; Georgakakis et al. 2004)**
- In the current deepest X-ray surveys, galaxies comprise a MINORITY of X-ray sources and make <5% of the diffuse XRB **(e.g., Hornschemeier et al. 2002; Persic & Raphaeli 2003)**

Snapshot of Science Results from Deep X-ray Surveys

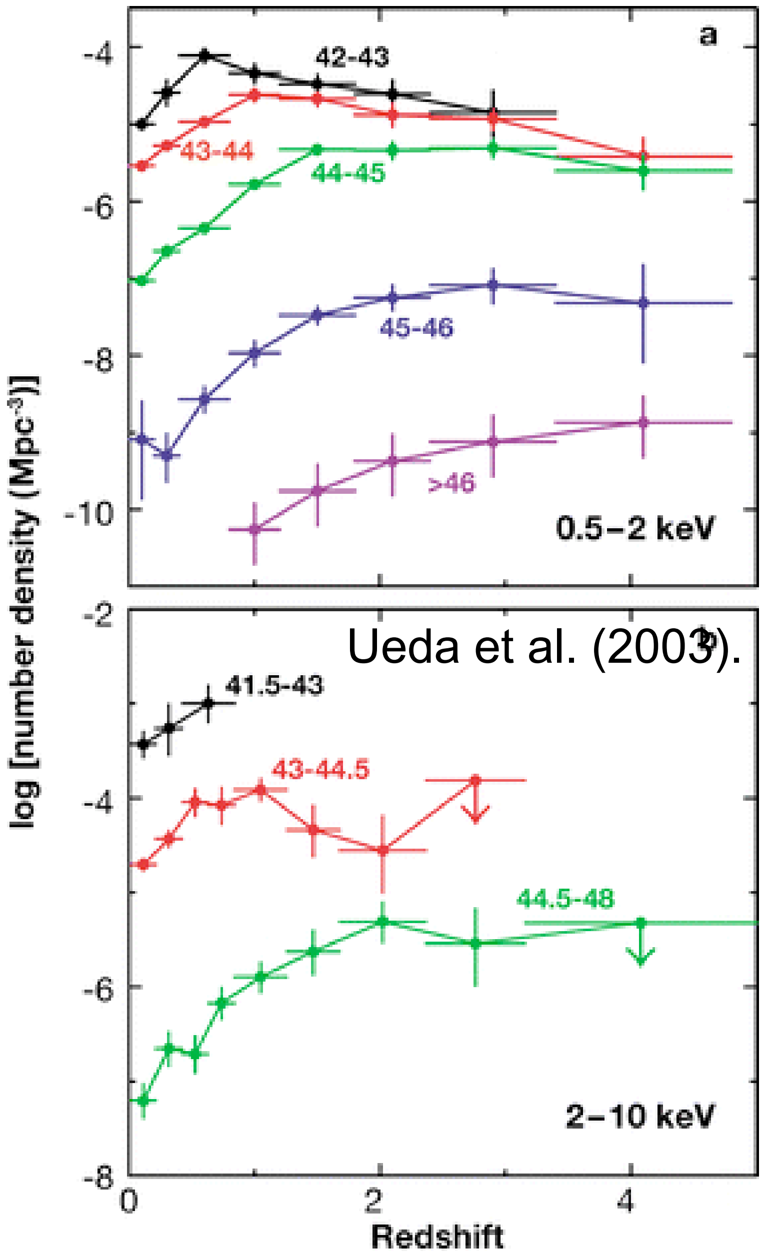
“When” was the CXRB made?



Barger et al. 2005

- It appears that the bulk of the CXRB was produced at relatively modest redshift (z<1; e.g., Barger et al. 2005)
- The CXRB is dominated by Seyfert-luminosity AGN (rather than the extremely luminous QSOs)

Hasinger, Miyaji & Schmidt (2005).



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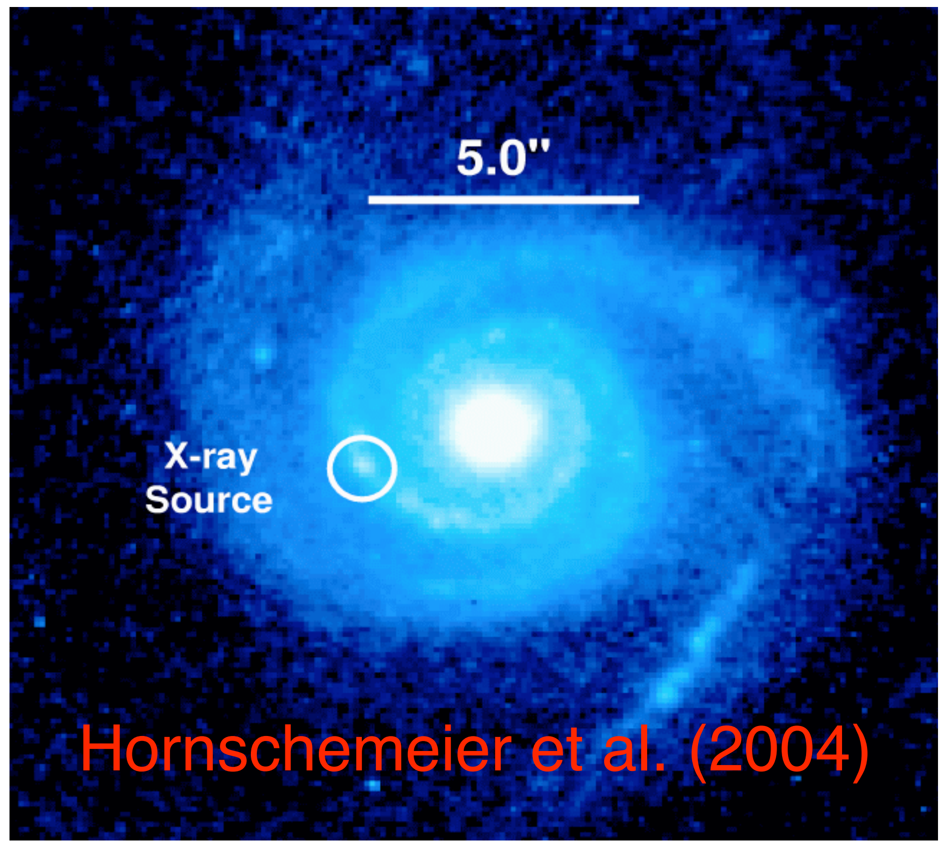
Cosmic Downsizing

- X-ray surveys result (discovered in X-rays first!)
- Massive black holes actively accreting at early times in Universe

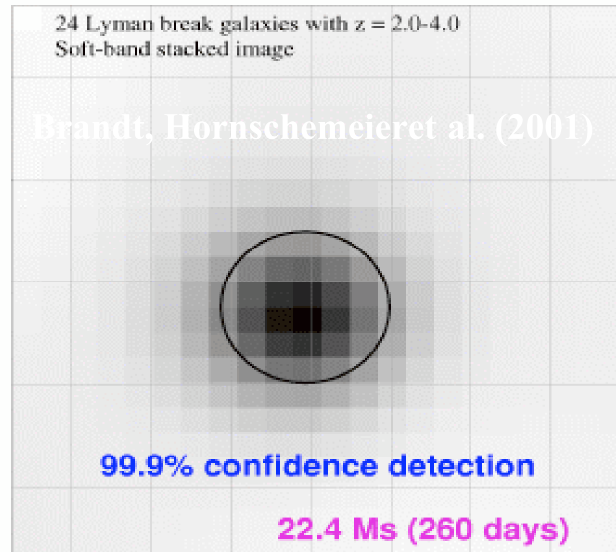
X-ray emission detected from many "normal" galaxies

- "Normal" galaxy = … galaxy whose X-ray emission is dominated by binaries, hot gas, etc. rather than a luminous AGN
- Can use X-ray emission as tracer of global star formation history of the Universe

Distant X-ray detected galaxy (z~0.1)



Beyond the faintest limits:
X-ray Emission from starbursts at z~3



- Take individually UNDETECTED Chandra sources, owing to good Chandra PSF and low background, stack the X-ray data to search for an average signal
- Stacking analysis:
  $\langle L_X \rangle \approx 1\text{-}3 \times 10^{41}$ erg s^{-1} (2-8 keV;
  Brandt, Hornschemeier et al. 2001; Nandra et al. 2002; Lehmer et al. 2005)
- Independent verification of UV methodology for measuring extinction at high z
  (Seibert, Meurer & Heckman 2001)
- Recently has been extended to even higher redshift (z~4) by Lehmer et al. (2005)

X-rays provide one of few direct cross-checks to UV-derived SFRs at z≥3

Some handy resources
& a few notes

REALLY X-ray faint sources: *Did I detect anything??*

- For faint sources (<10 counts on-axis), multiwavelength counterparts provide extra assurance of reality. Advanced tools like ACIS_EXTRACT should be used to evaluate PSF at large Chandra off-axis angles
- For ratios of low numbers of counts: recommend Lyons' method (see scanned pages from Niel Brandt's webpage at end of this talk)
- Useful reference : Kraft, Burrows & Nousek (1991) - upper limits given LOW numbers of counts, including look-up tables

X-ray Survey Tools/Resources

- HEASARC (http://heasarc.gsfc.nasa.gov)
  - Includes many fully-reduced all-sky (or wide-field) survey X-ray catalogs (RASS, ASCA)
  - Can easily search multiple catalogs
- XASSIST webpage (http://xassist.pha.jhu.edu)
  - Automatic reduction of many individual Chandra fields --> includes images & X-ray source catalogs as well as multiwavelength identifications
- ACIS_EXTRACT (http://www.astro.psu.edu/xray/docs/TARA/)
  - Top-notch IDL program that allows one to deal with large numbers of point and diffuse sources observed with the ACIS instrument
  - Wrapper for CIAO tools like mkpsf, etc.

BONUS:

X-ray K corrections

for Power Law Spectra

(see also Ptak et al. 2007 appendix on X-ray k-corrections for thermal plasmas)

X-ray bandpass at high *z*

- Most AGN are power-law sources in the X-ray: a few handy equations result for converting bandpasses & flux at high-z
- Take a power-law spectrum:

$$N_\nu(\nu) = N(\nu_0)\left(\frac{\nu}{\nu_0}\right)^\Gamma$$

rest-frame photon flux (photons/s*Hz)

$$L_{\nu_1\nu_2} = \int_{\nu 1}^{\nu_2} N_\nu(\nu)\cdot h\nu\, d\nu$$

erg/s

$$n_\nu(\nu) = \frac{N_\nu(\nu\,[1+z])\cdot(1+z)^2}{4\pi D_L^2}$$

observed photon flux (photons/s*Hz)

X-ray Bandpass at High-z

- Handy relations for X-ray bandpasses at high-z

$$L_{E_3 E_4} = \begin{cases} \frac{f_{E_1 E_2} \cdot 4\pi D_L^2}{(1+z)^{2+\Gamma}} \cdot \frac{E_4^{\Gamma+2} - E_3^{\Gamma+2}}{E_2^{\Gamma+2} - E_1^{\Gamma+2}} & : \quad \Gamma \neq -2 \\ f_{E_1 E_2} \cdot 4\pi D_L^2 \cdot \frac{\ln \frac{E_4}{E_3}}{\ln \frac{E_2}{E_1}} & : \quad \Gamma = -2 \end{cases}$$

$L_{E_3 E_4}$: rest-frame luminosity in bandpass [E_3,E_4]

$f_{E_1 E_2}$: observed-frame energy flux in bandpass [E_1,E_2]

X-ray Bandpass at High-z

- Example: for Γ=2 power-law, if we "match" the observed and rest-frame bandpasses, no k-correction is needed:

$$L_{E_3 E_4} = \begin{cases} \frac{f_{E_1 E_2} \cdot 4\pi D_L^2}{(1+z)^{2+\Gamma}} \cdot \frac{E_4^{\Gamma+2} - E_3^{\Gamma+2}}{E_2^{\Gamma+2} - E_1^{\Gamma+2}} & : \quad \Gamma \neq -2 \\ f_{E_1 E_2} \cdot 4\pi D_L^2 \cdot \frac{\ln \frac{E_4}{E_3}}{\ln \frac{E_2}{E_1}} & : \quad \Gamma = -2 \end{cases}$$

L(2-8 keV) = f(0.5-2 keV) * $4.0\pi D_L^2$

E_1 = 0.5 (keV), E_2 = 2 (keV) :OBSERVED
E_3 = 2 (keV), E_4 = 8 (keV) :REST-FRAME

Lyons' Method for Calculating Errors on Ratios

Thus a 3% error in x and a 4% error in y, assumed as usual to be uncorrelated, would combine to give a 5% error in f.

Because eqn (1.24) is in general not linear in x and y, eqn (1.26) will be accurate only if the fractional errors are small.

1.7.3 The General Case

There are two approaches that can be applied for a general formula

$$f = f(x_1, x_2, \ldots, x_n) \tag{1.28}$$

which defines our answer f in terms of measured quantities x_i each with its own error σ_i. Again we assume the errors on the x_i are uncorrelated.

In the first, we differentiate and collect the terms in each independent variable x_i. This gives us*

$$\delta f = \frac{\partial f}{\partial x_1}\delta x_1 + \frac{\partial f}{\partial x_2}\delta x_2 + \cdots + \frac{\partial f}{\partial x_n}\delta x_n. \tag{1.29}$$

As in our earlier examples, we then square and average over a whole series of measurements, at which point all the cross terms like $\overline{\delta x_1 \delta x_2}$ vanish because the different x_i are uncorrelated. We finally obtain

$$\sigma_f^2 = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2 \sigma_i^2. \tag{1.30}$$

X

This gives us the answer σ_f in terms of the known measurement errors σ_i. As with products and quotients, if f is non-linear in the x_i, this formula requires the errors σ_i to be small. (See problem 1.6.)

The alternative approach is applicable for any size errors. It consists of the following steps.

Useful!

(i) Calculate f_o as the value of f when all of the x_i are set equal to their measured values.

(ii) Calculate the n values f_i, which are defined by

$$f_i = f(x_1, x_2, \ldots, x_i + \sigma_i, \ldots, x_n),$$

i.e. where the ith variable is increased from its measured value by its error.

(iii) Finally obtain σ_f from

$$\sigma_f^2 = \sum (f_i - f_o)^2, \tag{1.31}$$

* The curly letter ∂ 's in eqn (1.29) (and later in (1.34)) mean that we should differentiate *partially* with respect to the relevant variable. Appendix 2 contains a brief explanation of partial differentiation.

i.e. we combine in quadrature all the individual deviations caused by moving each variable (one at a time) by its error.

To the extent that the errors are small, this approach should give the same answer as the previous one. For larger errors, the numerical method will give more realistic estimates of the errors. Furthermore, by moving each variable in turn both upwards and downwards by its error, we can deduce upper and lower error estimates for f which need not be identical. Thus, if

$$f = \tan x$$

and

$$x = 88 \pm 1°$$

we obtain

$$f = 29^{+29}_{-10}$$

as compared with

$$f = 29 \pm 14$$

from using eqn (1.30).

When the errors are asymmetric, it is a clear indication that the distribution of f is not Gaussian. Then we should be careful about how we calculate the significance of being, say, two or more errors away from some specified value.

1.8 Systematic errors

In Section 1.9, we shall consider the measurement of a resistance by the method discussed earlier in Section 1.2. We assume that the experiment produced the following results:

$$\left.\begin{aligned} R_1 &= (2.0 \pm 0.1\ \mathrm{k\Omega})\ \pm 1\%, \\ V_1 &= (1.00 \pm 0.02\ \text{volts})\ \pm 10\%, \\ V_2 &= (1.30 \pm 0.02\ \text{volts})\ \pm 10\%, \end{aligned}\right\} \tag{1.32}$$

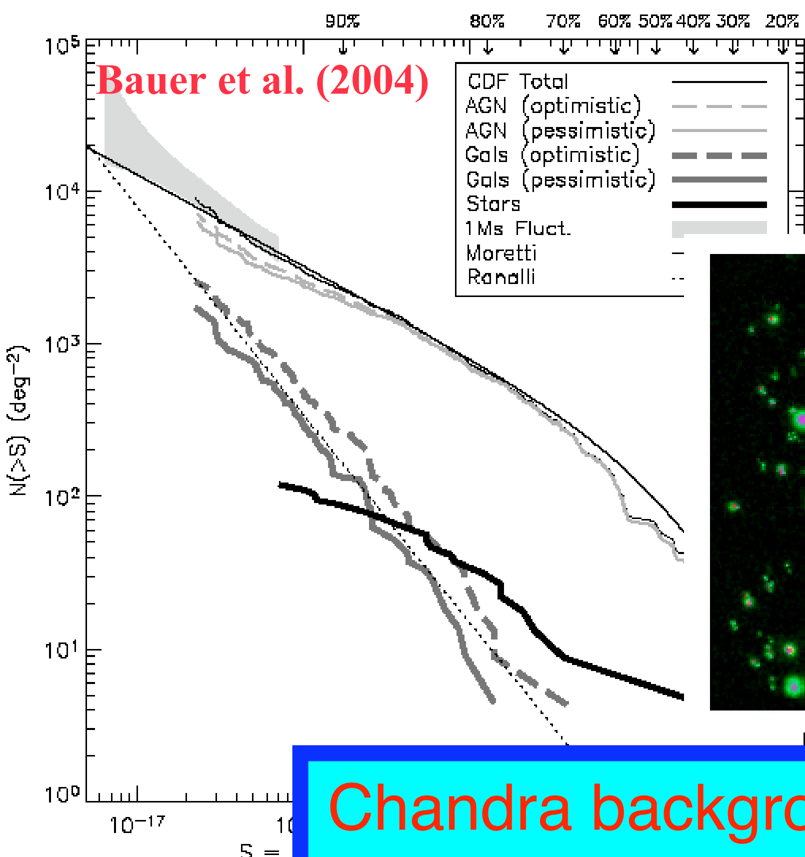
where in each case the first errors are the random reading ones, and the second are the possible systematic errors in the various meters.

Although random and systematic errors are different in nature, we may want the overall error estimate as a single figure, rather than expressed separately as above. Then we should add them in quadrature, since reading and calibration errors are uncorrelated. This yields

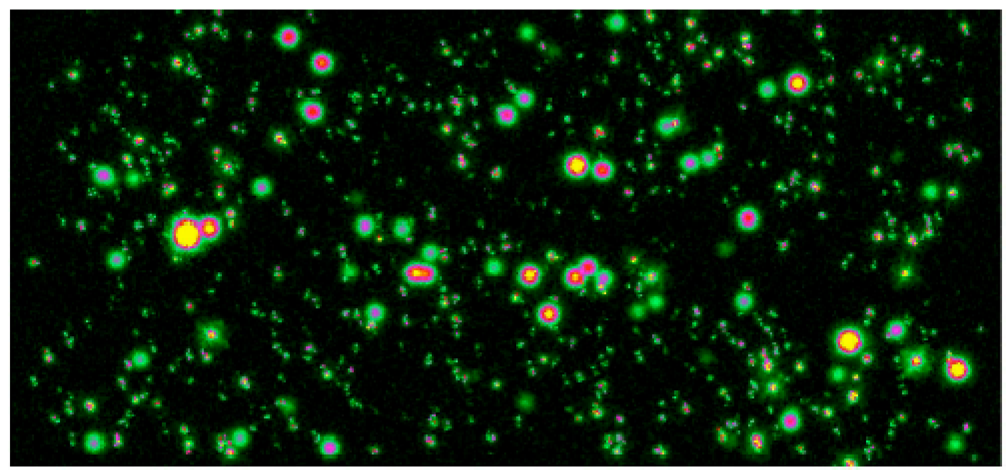
Finale:

Glimpse of the future of X-ray surveys

Going deeper in the X-ray band



Ultra-deep X-ray survey
($\leq 10^{-18}$ erg cm^{-2} s^{-1})



Chandra background is less than
1 count per pixel every ten days
Chandra can reach depths of (>5 Ms)